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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(81)91001-7

FISSION PROBABILITY OF THE IAR IN THE ACTINIDE REGION STUDIED VIA THE (^{3}He, tf) REACTION

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Received 27 July 1981

The widths and total fission probabilities, including first-, second- and third-chance fission of the IAR in ^{232}Pa and ^{238}Np have been measured via the reactions (^{3}He, t) and (^{3}He, tf). The results are: $\Gamma = 306 \pm 20$ keV, $P_f = 0.19 \pm 0.01$ for ^{232}Pa and $\Gamma = 380 \pm 40$ keV, $P_f = 0.30 \pm 0.04$ for ^{238}Np. Values for the spreading widths, $\Gamma^{\downarrow}$ are deduced. Global systematics of $\Gamma^{\downarrow}$ with mass number is indicated.

The decay of isobaric analog resonances (IAR) has been studied mostly in light and medium mass nuclei. For heavier nuclei ($A > 100$) little is known. A commonly used method is to measure the excitation function for (in)elastic proton scattering which yields total widths and decay widths for the open proton channels. Such an experiment has been done by Latzel and Paetz [1] to study IAR's in ^{208}Bi. Recently the decay of the ^{208}Pb(gs) analog has been studied by Gaarde et al. [2] via the reaction ^{208}Pb(^{3}He, tp). The results of the two experiments agree well and ^{208}Bi is probably the best studied case for heavy nuclei. The IAR(0^+) decays for 61% to low-lying states in ^{207}Pb by direct proton emission. This determines its escape width $\Gamma^{\uparrow}$. Through the Coulomb interaction it mixes with states of lower isospin and acquires also a spreading width $\Gamma^{\downarrow}$. Experimentally $\Gamma^{\downarrow}$ can be obtained indirectly as the difference $\Gamma_{tot} - \Gamma^{\uparrow}$, or directly by measuring the widths of decay channels other than proton decay. This is, e.g., the neutron channel. It is the aim of this letter to show that in very heavy nuclei the spreading width may also be measured directly via the fission probability.

We report on a measurement of the total width and fission probability of the IAR in ^{232}Pa and ^{238}Np via the reaction (^{3}He, tf).

A metallic ^{232}Th target of 0.49 mg/cm^2 thickness and a ^{238}U-oxide carbon backed target, 1.2 mg/cm^2 thick in ^{238}U, were bombarded with a 81 MeV momentum analyzed ^{3}He beam from the KVI cyclotron. Tritons were detected and identified in the QMG/2 magnetic spectrograph at $\theta = 0°$. The solid angle was 7.5 msr. The beam was stopped in a Faraday cup inside the first dipole magnet. Two thermo-electrically cooled silicon surface-barrier fission detectors were mounted on opposite sides of the beam at $\theta_{lab} = 145°$. Each subtended a solid angle of 130 msr with the target.

In fig. 1 a singles triton spectrum (top) is shown from the ^{232}Th(^{3}He, t)^{232}Pa reaction. The IAR stands out over a continuous background. A fit with a Breit–Wigner line shape is indicated. The presence of small amounts of ^{12}C and ^{16}O in the target provides a calibration of both energy and total resolution, through the excitation of the ^{12}N(gs) and ^{16}F($E_x = 0.424$) states. This total resolution is only 40 keV. The excita-

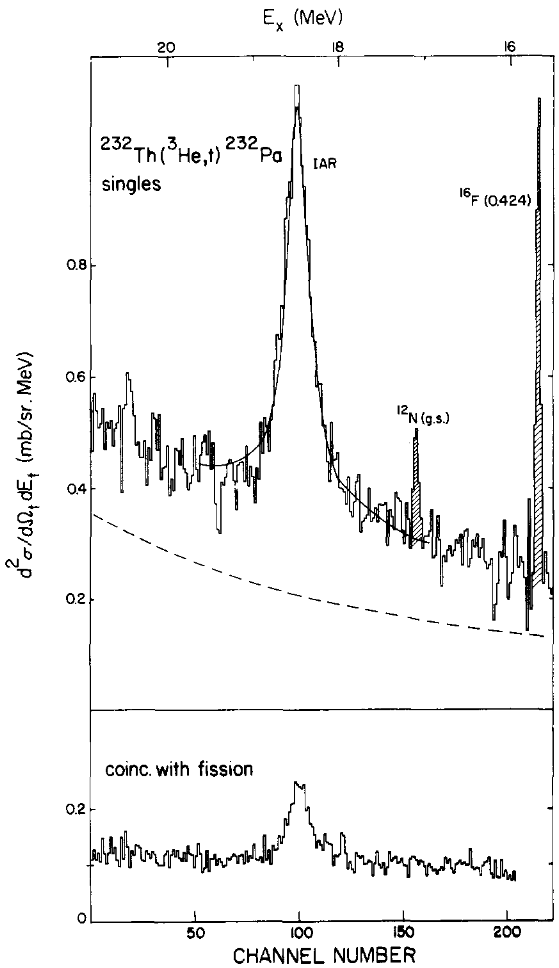

Fig. 1. Top: singles triton spectrum at $\theta = 0°$ from the reaction ^{232}Th(^{3}He, t)^{232}Pa. Bottom: the triton spectrum, coincident with fission fragments, integrated over the solid angle of the fission fragments. The dashed line in the singles spectrum indicates the shape of the break-up transfer component (see text).

tation energy of the IAR is found to be $E_x = 18.48 \pm 0.02$ MeV with a total width $\Gamma = 306 \pm 20$ keV.

In the bottom part of fig. 1 the triton spectrum as obtained in coincidence with fission fragments is shown. Since the spin of the IAR is $I^\pi = 0^+$, fission fragments are emitted isotropically. Thus the double differential cross section (fig. 1, bottom) is obtained by integrating over the solid angle for the fission fragment, neglecting the very small centre-of-mass to laboratory-frame correction

$$d^2\sigma(\text{coinc.})/dE_t d\Omega_t = 2\pi d^3\sigma/dE_t d\Omega_t d\Omega_f. \qquad (1)$$

A factor $\frac{1}{2}$ has been included to take care of the fact that each decay gives two fission fragments.

The total fission probability of the IAR is obtained from the ratio of the peak areas above the smooth backgrounds in the coincidence and the singles spectrum. The result is $P_f(^{232}\text{Pa(IAR)}) = 0.19 \pm 0.01$. The parameters of the IAR in ^{238}Np obtained similarly are listed together with those of ^{232}Pa in table 1.

The wave function of the IAR is schematically represented by

$$|(\text{IAR})\rangle = \alpha_{T_>} |T_>\rangle + \alpha_{T_<} |T_<\rangle, \qquad (2)$$

where $T_> = (N-Z)/2$ and $T_< = (N-Z-2)/2$; N and Z refer to the target nucleus.

The second term in eq. (2) arises from the mixing of the $T_>$ component with states of lower isospin through the Coulomb interaction. Disregarding γ-decay the width of the IAR, in its most general form, is given by:

$$\Gamma = \sum_{T=T_<}^{T_>} \alpha_T^2 [\Gamma_p(T) + \Gamma_{2p}(T) + \Gamma_n(T) + \Gamma_{2n}(T) + \Gamma_{np}(T) + \Gamma_{pn}(T) + \Gamma_f(T) + \Gamma_{pf}(T) + \Gamma_{2pf}(T) + \Gamma_{nf}(T) + \Gamma_{2nf}(T) + \Gamma_{npf}(T) + \Gamma_{pnf}(T)]. \qquad (3)$$

Here, $\Gamma_\alpha(T)$ is the partial decay width into channel α for a pure state $|T\rangle$. For $T = T_>$, neutron decay to energetically allowed states in the $(A-1)$ nucleus is isospin forbidden. Fission, preceded by proton decay, is allowed but the maximum available energy for proton decay that leaves the daughter nucleus, ^{231}Th, with an excitation energy above its fission barrier is much lower than the Coulomb barrier and therefore the proton transmission coefficients are vanishingly small. If for the pure state $|T\rangle$ the mapping $|T_>\rangle = |\text{IAS}\rangle = T_-|0\rangle$, where $T_- = \Sigma_i t_-(i)$ is the isospin lowering operator, persists for all values of the deformation parameter, the IAS, like its parent state, effectively experiences a barrier that inhibits fission. This very plausible argument means that also $\Gamma_f(T_>)$ vanishes.

For $T = T_<$ all terms involving proton emission are much smaller than the terms involving only neutron decay and fission, because of the Coulomb barrier. In conjunction with $\alpha_{T_<}^2 \ll \alpha_{T_>}^2$ this finally reduces eq. (3) to

Table 1
Measured parameters of the IAR.

Element	E_x (MeV)	Γ_{tot} (keV)	P_f	$\Gamma^{\downarrow}_{exp}$ a) (keV)	$\Gamma^{\downarrow}_{calc}$ b) (keV)	$\Gamma^{\downarrow}_{calc}$ c) (keV)
^{232}Pa	18.48 ± 0.02	306 ± 20	0.19 ± 0.01	90 ± 20	82	329
^{238}Np	19.09 ± 0.04	380 ± 40	0.30 ± 0.04	142 ± 37	87	350

a) Obtained via eqs. (7) and (8). b) Calculated with V_M = 170 MeV and Γ_M = 15 MeV with the matrix element (m.e.) from the hydrodynamic model. c) As b) with the m.e. taken from the microscopic model.

$$\Gamma = \alpha^2_{T_>}\Gamma_p(T_>) + \alpha^2_{T_<}[\Gamma_n(T_<) + \Gamma_{2n}(T_<) + \Gamma_f(T_<) + \Gamma_{nf}(T_<) + \Gamma_{2nf}(T_<)]$$
$$= \Gamma_p + \Gamma_n + \Gamma_{2n} + \Gamma_f + \Gamma_{nf} + \Gamma_{2nf}. \quad (4)$$

It follows that the escape width is determined by proton decay to low-lying states only, or

$$\Gamma^{\uparrow} = \Gamma_p. \quad (5)$$

The partial decay widths involving neutron decay and first-, second- and third-chance fission are associated with mixing-in of $T_<$ components and together constitute the spreading width

$$\Gamma^{\downarrow} = \Gamma_n + \Gamma_{2n} + \Gamma_f + \Gamma_{nf} + \Gamma_{2nf}. \quad (6)$$

Defining

$$P_f = (\Gamma_f + \Gamma_{nf} + \Gamma_{2nf})/\Gamma$$

and

$$P_f(T_<) = (\Gamma_f + \Gamma_{nf} + \Gamma_{2nf})/\Gamma^{\downarrow}, \quad (7)$$

one finds

$$\Gamma^{\downarrow} = \Gamma P_f/P_f(T_<). \quad (8)$$

Γ and P_f are the measured quantities in the present experiment. One would like to identify $P_f^{tot}(T_<)$ with the fission probability of the continuum spectrum under the IAR. This, however, can not be done directly. It has become clear recently [3–5] that the triton spectrum contains a considerable component due to a quasi-free neutron pickup reaction proceeding through (^{3}He, pd) (pd, pt). This process excites precisely those states in ^{231}Th that are also populated in a neutron pickup reaction, e.g. ^{232}Th(d, t)^{231}Th. Most of the neutron pickup strength is located below the fission barrier in ^{231}Th, and the above process does not contribute to the fission channel.

A reliable value for $P_f(T_<)$ can, however, be obtained by a statistical calculation that uses the fission barriers and the neutron separation energies in the nuclei ^{230,231,232}Pa. The calculation is essentially based on the available phase spaces for the decay modes n, 2n, f, nf and 2nf, constrained to add up to unity probability [6], Fission barriers and level densities are tuned to reproduce the fission probability observed at lower excitation energies in ^{232,231,230}Pa as measured by Gavron et al. [7]. We find for ^{232}Pa

$$P_f(T_<) = 0.65, \quad \text{at } E_x = 18.5 \text{ MeV}$$

and estimate this value to be accurate within 20%.

In fig. 1 the shape of the continuum, corresponding to the breakup transfer process is indicated. It has been obtained by subtracting the coincident spectrum, multiplied by $[P_f(T_<)]^{-1}$, from the singles spectrum, where $P_f(T_<)$ has been calculated as described above. With eq. (8) one obtains

$$\Gamma^{\downarrow}(\text{IAR}) = 90 \pm 20 \text{ keV}, \quad \text{for } ^{232}\text{Pa}.$$

Similarly using $P_f(T_<)$ = 0.80 from the statistical calculation we find

$$\Gamma^{\downarrow}(\text{IAR}) = 142 \pm 37 \text{ keV}, \quad \text{for } ^{238}\text{Np}.$$

It has been argued [8–11] that the spreading width is mainly due to mixing with the charge-exchange isovector monopole resonance (M). In that case the spreading width of the IAR is given by

$$\Gamma^{\downarrow} = |\langle M|H|\text{IAR}\rangle|^2 \frac{\Gamma_M}{(E_M - E_{IAR})^2 + (\Gamma_{M/2})^2}. \quad (9)$$

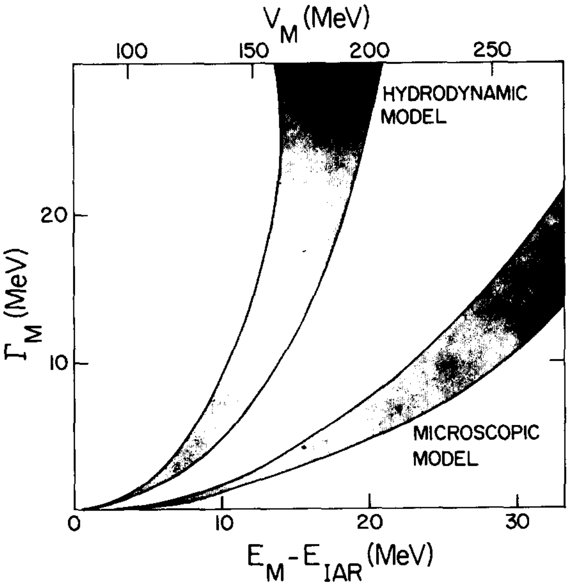

Fig. 2. Regions of excitation energy (E_M) and damping width (Γ_M) for the charge-exchange isovector monopole, allowed on the basis of our experimental value for $\Gamma^{\downarrow}$ of the IAR in ^{232}Pa within its errors. Results from the hydrodynamic and microscopic model are indicated.

The matrix element is obtained from a hydrodynamic model [9,12] as

$$|\langle M|H|IAR\rangle|^2 = \frac{2T-1}{2T(2T+1)}\,\frac{Z^2}{100}\ \mathrm{MeV}^2, \tag{10}$$

or from the microscopic model of Auerbach [13] as

$$|\langle M|H|IAR\rangle|^2$$
$$= 1.06\times 10^{-2}\,\frac{2T-1}{2T(2T+1)}\,Z^2 N A^{-2/3}\ \mathrm{MeV}^2. \tag{11}$$

In fig. 2 are indicated the regions that, within the limits of uncertainty of the experiment, correspond to the allowed values for the excitation energy and the damping width of the charge-exchange isovector monopole resonance, for both choices of the matrix element.

The energy difference may be written as [12]

$$E_M - E_{IAR} = V_M A^{-1/3} - 110(T/A). \tag{12}$$

The second term is the difference in symmetry potential for a neutron and a proton; V_M has been estimated on the basis of a hydrodynamic model to be $V_M \approx 170$ MeV [12]. In fact this calculation was done for $N = Z$

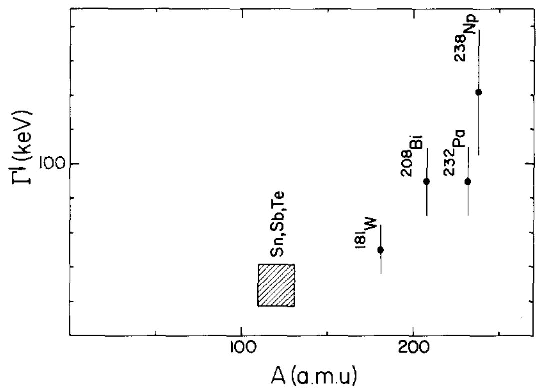

Fig. 3. Experimental values of $\Gamma^{\downarrow}$ (IAR) versus mass number for $A > 100$.

nuclei and pertains to the isovector monopole resonance and not to the charge-exchange isovector monopole resonance. Since, however, in a $2\hbar\omega$ Tamm–Dancoff picture both resonances have the same number of components, a similar degree of collectivity and a similar value for V_M might be expected for the two resonances.

The damping factor Γ_M occurring in eq. (9) is usually calculated in RPA with a Skyrme interaction [14–17]. Values of 10–15 MeV seem to be typical for nuclei in this mass region.

These considerations favour the value for the matrix element from the hydrodynamic model over that from the microscopic model. If one adheres to a value $V_M \approx 170$ MeV, the latter model would imply a damping width of about 4 MeV. In that case the charge-exchange isovector monopole resonance should probably have been seen in recent (p,n) studies at high energies [18]. Also the value of $\Gamma^{\downarrow}$, obtained for the IAR in ^{238}Np is reasonably reproduced by the hydrodynamic model (table 1). This model gives slightly lower values than experiment and leaves room for additional spreading through doorways other than the charge-exchange isovector monopole.

In fig. 3 experimentally determined spreading widths of the IAR are plotted versus mass number for $A \geqslant 100$ for cases in which $\Gamma^{\downarrow}$ has been measured directly, (^{232}Pa, ^{238}Np) or indirectly via Γ and $\Gamma^{\uparrow}$, such as ^{208}Bi [1,2] and ^{181}W [19].

In the region of the Sn, Sb and Te isotopes many experiments have been done where either it has been argued that $\Gamma^{\uparrow}$ might be small and thus $\Gamma \approx \Gamma^{\downarrow}$ [20], or where $\Gamma^{\uparrow}$ has been estimated from proton decay to the ground state only [21]. These results, which are to be considered upper estimates for $\Gamma^{\downarrow}$ are indicated as a hatched area.

The global behaviour of $\Gamma^{\downarrow}$ versus A is smooth, as is to be expected from the hydrodynamic model.

This work was performed as part of the research program of the "Stichting voor Fundamenteel Onderzoek" (FOM) with financial support from the "Nederlandse Organisatie voor zuiver Wetenschappelijk Onderzoek" (ZWO).

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